REFRIGERATING FLUID WITH A LOW GLOBAL WARMING POTENTIAL FOR AUTOMOTIVE AIR CONDITIONING SYSTEMS IN SUMMER

by

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Original scientific paper
https://doi.org/10.2298/TSCI200308045M

Refrigerants with low global warming potential (GWP) are much needed in automotive air conditioning systems. This paper compares two refrigerants, R134a (GWP=1300) and R513A (GWP = 573) experimentally. The results show that the latter has lower cooling capacity, lower COP and lower discharge temperature than the former, revealing that R513A is a promising replacement of its high GWP partner.

Key words*: automotive air conditioning systems, micro-channel heat exchanger, R513A, R134a*

Introduction

The problem of environmental pollution has become increasingly prominent, and it has become a popular research topic in the refrigeration and air conditioning field to find a new environmentally friendly refrigerant. In recent years, the international community has signed relevant regulations to control the use and emission of hydrofluorocarbon (HFC) refrigerants. In 2014, the EU amended the F-Gas Regulation, banning completely the use of high GWP HFC refrigerants in new air-conditioning products. In October 2016, the international community reached the *Kigali Programme* based on the framework of the Montreal Protocol, which further promoted the reduction of high GWP HFC refrigerants. The Kigali Amendment required developed countries to phase out HFC by 2019 and developing countries to freeze and suspend HFC between 2024 and 2028 [1].

The R134a is an HFC refrigerant, and its GWP value is as high as 1300, which represents a strong greenhouse effect, however, it is still widely used in small refrigeration devices, automotive air conditioning systems (MAC) and heat pump units [2]. Therefore, the replacement of R134a has become an urgent issue for an immediate treatment. Potential low GWP refrigerants mainly include hydrofluoroolefins (HFO) and the related mixed refrigerants [3].

The HFO with low GWP are considered as an ideal alternative to R134a. Compared with R134a, the pure refrigerants, R1234yf, and R1234ze, have slightly low cycle performance in the same refrigeration system [4]. Researches have mainly focused on R1234yf as a replacement for R134a in MAC [5-7], showing that the cooling capacity and COP of R1234yf were

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lower than those of R134a. The R1234yf can also be used as a substitute refrigerant for R134a in small refrigeration devices such as household refrigerators. Belman-Flores [8] resented an experimental study for three identical domestic refrigerators using R1234yf as a drop-in replacement for R134a. The results showed that R1234yf presented an average (for the three refrigerators) of 0.4 °C for the fresh food compartment and 1.2 °C for the freezer among different charges with respect to R134a. Aprea *et al.* [9] carried out an experimental study on the performance of R1234yf and R134a in a domestic refrigerator. The results showed that R1234yf has allowed for reducing of a 7.3% the pull-downtime and of a 23% the duty cycle. The power consumption and cooling rate of R1234yf were similar to those of the R134a system.

Recently, mixed refrigerants have become a popular research topic. Deveciolu *et al.* [10] compared the thermophysical properties of R450A, R513A, and R134a. The results showed that R450A and R134a had the closest performance under specific conditions. In addition, the viscosity of R450A and R513A was lower than that of R134a. Meng *et al.* [11] studied the feasibility of replacing R134a with a new mixed refrigerant R1234yf/R134a (mass fraction ratio 89:11) in MAC using micro-channel heat exchangers. The experimental results showed that the cooling capacities of the mixed refrigerants R1234yf/R134a and R134a were similar. The COP was 4-9% lower than that of R134a. It was concluded that the mixed refrigerant R1234yf/R134a could be directly used in the R134a original MAC. Yang *et al.* [12] and Mota-Babiloni *et al.* [13] compared R513A and R134a, and experiments showed that the performance of R513A in the refrigeration system was similar to that of R134a. In the study of Devecioglu *et al.* [14], R444A and R445A had lower COP, but the use of these mixtures in R134a systems was recommended if the highest COP was not the key objective. Mota-Babiloni *et al.* [15] investigated ARM-41a, D-4Y, XP-10, and ARM-42a as alternatives to R134a, revealing that among the non-flammable options, the best results (cooling capacity and COP) were observed for ARM-41a. The experimental studies reviewed also showed good results for XP-10 and ARM-42a when substituting R134a.

In summary, R1234yf and R1234ze (E) show low cooling capacities and COP. In the mixed refrigerants study, the GWP is reduced to a certain extent, but these mixtures also have some shortcomings, such as flammability and an overabundance of mixtures, and leakage affects the operation performance. Compared to these mixed refrigerants, R513A is a competitive refrigerant. R513A is non-flammable and is a binary azeotropic refrigerant consisting of R134a and R1234yf with a mass fraction of 44/56. It runs stably in the refrigeration system and has little influence on the leakage. Studies have shown that R513A performs better than R1234yf. However, research on R513A as an alternative to R134a in MACs has not yet been reported. In this paper, the performance of R513A and R134a in summer was studied by building an MAC platform. It directly compares the performance of R513A to provide feasible suggestions for the selection of low GWP refrigerants in the automobile air conditioning industry.

Thermodynamic analysis

In order to calculate the thermodynamic cycle performance, the properties of the vapor compression system are calculated and analyzed on the P-H diagram. According to the temperature and pressure of each state point, the corresponding enthalpy and entropy values are obtained, and the thermodynamic cycle performance is calculated. In this paper, a thermodynamic cycle model under cooling mode are introduced for the MAC. The condensation temperature is 55 °C and evaporation temperature is 7 °C. The superheating and supercooling degree are 5 °C as typical working conditions. All the thermodynamic properties were obtained from the NIST database REFPROP 9.1 [16]. The main calculation formulas are derived from reference [17]. The main assumptions are:

- The isentropic efficiency and volumetric efficiency of the compressor are 0.75 and 0.8, respectively.
- The compressor has a constant stroke volume of 33 cc/rev and a constant speed of 3000 rev per minute.
- There is no pressure drop in the condenser, evaporator and connecting pipe.
- There is no heat exchange loss between the system and the outside world.
- The enthalpy of refrigerant before and after throttling valve is unchanged.

The simulation performance parameters of the three refrigerants in MAC are shown in tab. 1. The volumetric cooling capacities of R1234yf and R513A are lower than that of R134a. The volumetric cooling capacity of R513A is improved and is higher than that of R1234yf. The volumetric cooling capacity of the mixed refrigerant (R513A) is increased due to the large volumetric cooling capacity of R134a. The volumetric cooling capacity represents the cooling capacity in the same system. Table 1 shows that the variation trends of the cooling capacities of R1234yf, R513A, and R134a are similar to those of the volumetric cooling capacities. Compared with R134a, the pressure ratio of R1234yf and R513A is lower than that of R134a. The pressure ratio mainly affects the compressor volumetric efficiency. It can be concluded that when R1234yf and R513A replace R134a, the compressor volumetric efficiency of the two refrigerants is better. The mass-flow rates of R1234yf and R513A are higher than that of R134a. This occurs because the suction densities of R1234yf and R513A at the compressor inlet are higher. In terms of energy efficiency, the COP of R1234yf and R513A are smaller than that of R134a, while that of R513A is larger than that of R1234yf. This occurs because the COP of R134a is larger, and the addition of R134a to R1234yf can improve the COP of the mixed refrigerants. The compressor discharger temperatures of R1234yf and R513A are lower than that of R134a. Therefore, it can be predicted that the compressor life of the two refrigerants is longer when R1234yf and R513A replace R134a.

Table 1. Simulative performance of three refrigerants in cooling mode

Mode	Performance parameter	R1234yf	R513A	R134a
Cooling	Volumetric cooling capacity [kJm^{-3}]	1769.67	1850.59	1937.17
	Mass-flow rate [kg^{-1}]	102.21	93.83	84.78
	Pressure ratio	3.68	3.77	3.98
	Cooling capacity [W]	2919.95	3053.48	3196.34
	Power consumption [W]	895.71	909.13	926.40
	COP	3.25	3.35	3.45
	Compressor discharge temperature [°C]	62.72	68.13	72.63

Experiment

The lay-out of the experimental device is shown in fig. 1. The performance of MAC is tested in multi-functional simulation environment test system. The temperature and humidity can be adjusted by using the environment control box composed of cooling coil, heater, humidifier and fan. The enthalpy of air can be obtained by measuring the temperature of wet and dry balls before and after the heat exchanger. Air-flowing through the heat exchanger is driven by a blower. At the same time, the volumetric flow rate of the air is measured and calculated by a nozzle flowmeter. The air-side heat exchanger capacity is calculated according to the enthalpy difference and volumetric flow rate before and after the heat exchanger.

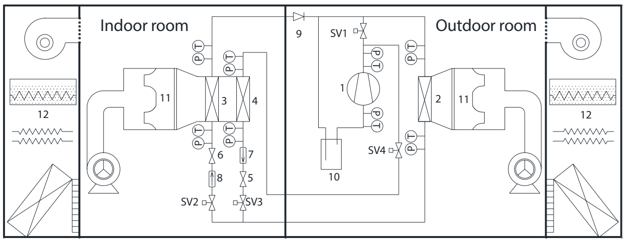

Figure 1. Lay-out of automotive air conditioning systems;
1 – compressor, 2 – out-car heat exchanger, 3 – in-car evaporator, 4 – in-car condenser, 5 and 6 – electronic expansion valve, 7 and 8 mass-flow meter, 9 – one-way valve, 10 – gas liquid separator, 11 – air measuring device, and 12 –air handling unit

The MAC are mainly composed of a compressor, two in-car micro-channel heat exchangers, an out-car micro-channel heat exchanger, two electronic expansion valves, two mass-flowmeters and several solenoid valves (SV). The main component parameters are shown in tab. 2. One of the in-car heat exchangers is used as an evaporator in cooling mode, while the other is used as a condenser in heating mode. The two in-car heat exchangers are integrated in the same air duct. The cooling mode is controlled by switching the SV. Specifically, under the cooling mode, SV3 and SV4 are closed, and SV1 and SV2 are opened. At this time, the refrigerant flow direction moves from the compressor outlet, to the out-car heat exchanger, to the mass-flowmeter, to the electronic expansion valve, to the in-car evaporator, to the gas-liquid separator, and finally back to the compressor inlet. The gas-liquid separator is set at the inlet of the compressor. To calculate the refrigerant side heat transfer capacity and compressor operating parameters, temperature and pressure measurement points are installed at the inlet and outlet of the compressor, the inlet and outlet of the out-car heat exchanger, the inlet and outlet of the in-car condenser and the evaporator.

Table 2. Specifications of the experimental set-up

Components	Specifications
Out-car heat exchanger	507.8 [W)]× 393 [H] × 16 [D] Micro-channel parallel flow structure
In-car condenser	252 [W] × 250 [H] × 40 [D] Micro-channel parallel flow structure
In-car evaporator	223.6 [W] × 159.8 [H] × 24 [D)] Micro-channel parallel flow structure
Compressor	Swash plate type (V_{dis} = 33 cc/rev)

The measurement and control system is composed of an Agilent data acquisition instrument, PLC and computer. The computer can control the opening of electronic expansion valves, the opening and closing of SV and the speed of compressors through instructions issued by PLC. Temperature, pressure and mass-flow data are mainly collected by the Agilent 34792A. The compressor power consumption is collected by AC and DC power measurement instrument acquisition. When the system is stable, the enthalpy of each point is obtained according to the measured temperature and pressure parameters. According to the experimental data processing formula from reference [11], the system running performance parameters of the refrigerant side are calculated. The effective experimental data are recorded by regulating the steps of the electronic expansion valve to attain the best COP of the MAC. During the test period, the total energy balance between the refrigerant side and the air side is approximately 5%.

The cooling mode is divided into nine working conditions, respectively, as shown in tab. 3. In cooling mode, the control parameters included compressor speed, inlet air temperature, relative humidity and air mass-flow rate. The test in cooling mode simulated the three working temperature conditions.

Table 3. Operating conditions in cooling mode

Working temperature conditions	Number	RPM [Revmin^{-1}]	Indoor room			Outdoor room	
			Dry bulb Temperature [°C]	Relative humidity [%]	Air mass-flow rate [kgmin^{-1}]	Dry bulb Temperature [°C]	Air mass-flow rate [kgmin^{-1}]
Low	1/2	2000/3000	27	45	5.5	30	28
	3	4000	27	45	8.2	30	31.8
Moderate	4/5	2000/3000	25	45	5.5	38	31.8
	6	4000	25	45	8.2	38	31.8
High	7/8/9	2000/3000/4000	38	45	8.2	43	31.8

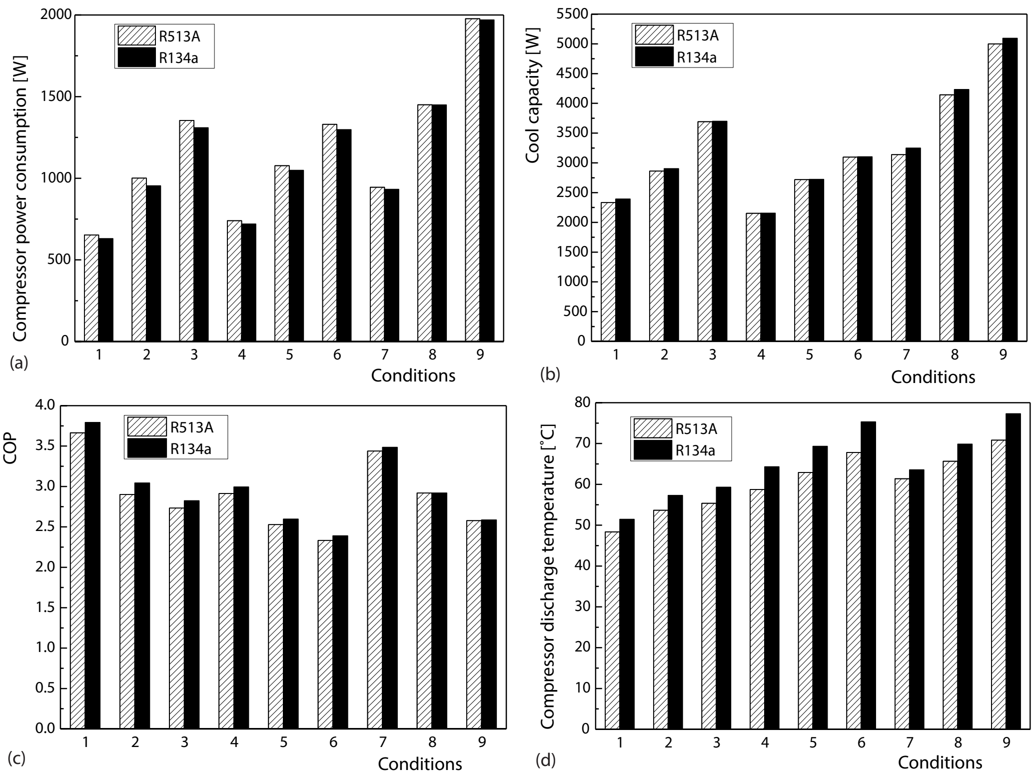

Figure 2. Experimental energy performance parameters under different working temperature conditions in cooing mode.; (a) compressor power consumption, (b) cooling capacity, (c) COP, (d) compressor discharge temperature

Results and discussion

The compressor power consumption of R513A and R134a in MAC is shown in fig. 2(a). The compressor power consumption of R513A is higher than that of R134a. The compressor power consumption of R513A is 4.5% and 3% higher than that of R134a under low and moderate temperature conditions, respectively. Under high temperature conditions, the compressor power consumption of R513A is basically the same as that of R134a. The compressor power consumption increases with increasing compressor speed. This is because an increase in the compressor speed leads to an increase in the mass-flow rate and compression ratio. Under high temperature conditions, the discharge pressure of R513A is lower than that of R134a, and the suction pressure of R513A is higher than that of R134a, which results in a relatively large compression ratio deviation. That is, the compression specific work of R513A is lower. The lower compression specific work compensates for the increase in compressor power caused by higher mass-flow, so the compressor power consumption of R513A is close to that of R134a. The compressor power consumption deviation between the two refrigerants is high under low temperature conditions. At low temperature conditions, the discharge pressure of R513A is higher than that of R134a, and the suction pressure of R513A is slightly higher than that of R134a. Under this condition, the compression specific work deviation of the two refrigerants is small. The mass-flow rate deviation plays a decisive role.

The cooling capacity of R513A and R134a in MAC is shown in fig. 2(b). Overall, the cooling capacity of R513A is similar to that of R134a. The results show that R513A is 1-2% smaller than R134a under all working conditions. The result can compare to that of Cho *et al.* [18], who used a similar experimental device to compare the system performance parameters of R1234yf and R134a in MAC. Experiments showed that the cooling capacity of R1234yf was approximately 4-7% lower than that of R134a. The cooling capacity of R513A in this paper is better than that of R1234yf because R513A is mixed with a larger volumetric cooling capacity of R134a.

The COP of R513A and R134a in MAC is shown in fig. 2(c). The COP of R513A is 3-6% lower than that of R134a under all conditions, respectively. The COP of R513A is lower than that of R134a because of the high compressor power consumption. The COP of the refrigerants decrease with increasing compressor speed. With increasing compressor speed, the compressor suction pressure decreases, while the discharge pressure increases, resulting in a lower evaporation temperature and higher condensation temperature, which reduces the latent heat of refrigerant in the evaporator and increases the compression specific work. This is why the COP decreases with increasing compressor speed. At low temperature conditions, the COP of condition 3 decreases slightly compared with that of condition 2. This occurs because the air mass-flow rate of the in-car and out-car heat exchangers increases with increasing compressor speed in working condition 3. The system runs well in this condition. Additionally, it can be obtained that the COP under high temperature and low temperature conditions are larger than those under moderate temperature conditions. This is due to the large difference between the indoor and outdoor temperatures under moderate conditions, resulting in a large difference between the evaporation temperature and condensation temperature, thus causing a decrease in COP. At high temperature conditions, the COP deviations of R513A and R134a are smaller. This occurs because the compressor power consumption deviation is smaller.

The compressor discharge temperature of R513A and R134a in MAC is shown in fig. 2(d). The average compressor discharge temperature of R513A is 6 °C lower than that of R134a under all conditions. The R513A has lower compressor discharge temperatures, which can improve the service life of the compressor. The compressor discharge temperature increases with increasing compressor speed. This occurs because the suction pressure decreases with increasing compressor speed.

The compression ratio of R513A and R134a in MAC is shown in fig. 3(a). The average compression ratio of R513A is 6% lower than that of R134a under all conditions. The compression ratio deviations of R513A and R134a are smallest at low temperature conditions and largest at high temperature conditions. This occurs because the thermodynamic properties show that under low temperature, the saturation pressure of R513A is larger than that of R134a, and under high temperature, the saturation pressure of R513A is lower than that of R134a. Under moderate temperature conditions, both refrigerants operate at a high compression ratio. This occurs because the indoor temperature and outdoor temperature difference is larger, resulting in a larger difference between the condensation pressure and the evaporation pressure.

The mass-flow rate of R513A and R134a in MACs is shown in fig. 3(b). The average mass-flow rate of R513A is 18% higher than that of R134a, respectively. The mass-flow rate increases with increasing indoor temperature. This occurs because the indoor temperature determines the evaporation pressure. A high indoor environmental temperature leads to a high evaporation pressure, thus causing a large suction density at the compressor inlet.

The compressor volumetric efficiency and global efficiency of R513A and R134a in MAC is compared, as shown in fig. 3(c). The compressor volumetric efficiency is mainly related to the volumetric coefficient, pressure coefficient, temperature coefficient and leakage coefficient. Under the same working conditions, the volumetric efficiency can reach a maximum value with increasing compressor speed. The compressor volumetric efficiency decreases when

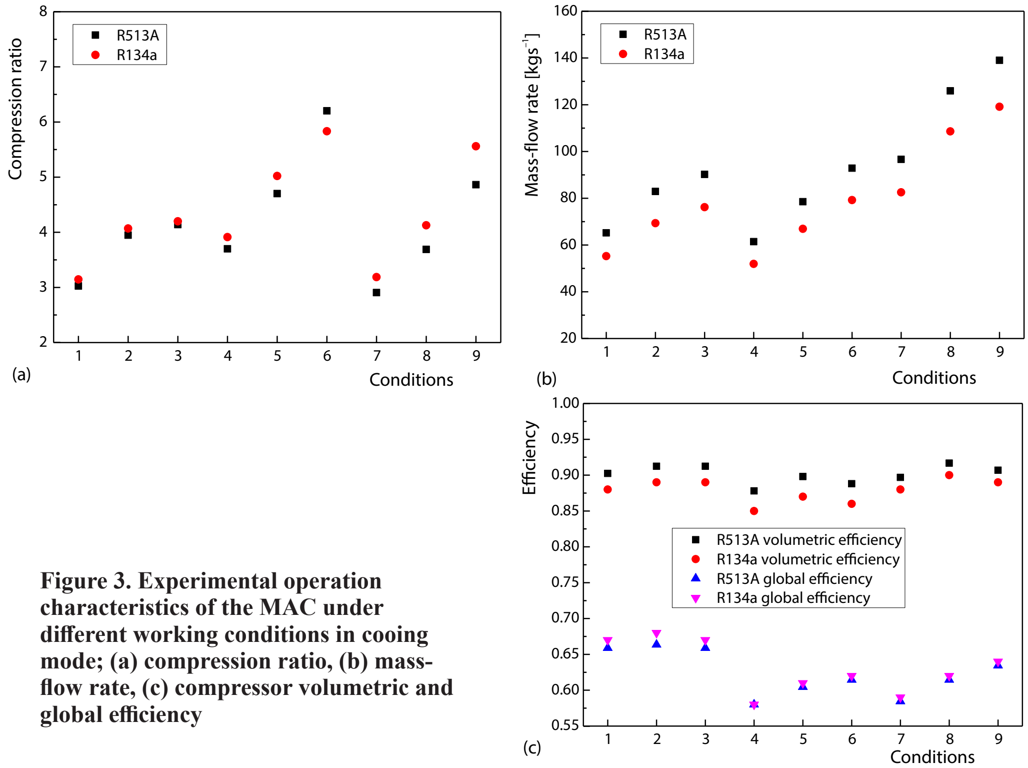

Figure 3. Experimental operation characteristics of the MAC under different working conditions in cooing mode; (a) compression ratio, (b) mass-flow rate, (c) compressor volumetric and global efficiency

the compressor speed is greater or less than the optimal value. Compared with conditions 1 and 2, 4 and 5, 7 and 8, the compressor volumetric efficiency has not reached its maximum value at 2000 rev per minute, so when the speed of the compressor reaches 3000 rev per minute, the compressor volumetric efficiency shows an upward trend. Compared with conditions 7-9, it can be obtained that the compressor volumetric efficiency has exceeded the optimum value at 4000 rev per minute, so it shows a downward trend. The compressor volumetric efficiency of R513A is 4% higher than that of R134a, respectively. This occurs because, as shown in fig. 3(a), the compressor ratio of R513A is lower than that of R134a, thus, the volumetric coefficients of R513A is larger under the same conditions.

The compressor global efficiency is a complex variable that includes three compressor efficiencies: isentropic efficiency, electrical efficiency, and mechanical efficiency. It establishes the relationship between the minimum compressor power consumption needed by the compressor to compress a refrigerant under specific operating conditions and the actual conditions. The compressor global efficiency under high temperature conditions is lower than that under low temperature conditions. This occurs because the compressor suction temperature is lower under low temperature conditions and higher under high temperature conditions. A higher compressor suction temperature leads to a decrease in the viscosity of the oil and an increase in friction loss. As a result, the global efficiency drops. Under moderate temperature conditions, although the compressor suction temperature is not higher, the compressor global efficiency is lower than that under high temperature conditions. This occurs because a compressor with a larger compression ratio has an adverse effect on the compressor under moderate temperature conditions. Figure 3(c) shows that the compressor global efficiencies of the two refrigerants are similar. Therefore, when R513A directly replace R134a in MACs, it has little effect on the compressor global efficiency. A compressor with R134a is also suitable for R513A.

Conclusions

A new type performance test bench of MAC was built and the comparative experiments of R513A and R134a under cooling mode were carried out. Based on the test results, the following conclusions can be drawn.

- The cooling capacity of R513A is similar to that of R134a, and the COP of R513A is 3-6% less than that of R134a.
- The average compressor discharge temperature using R513A is lower than that using R134a by approximately 5 °C.
- The average compressor volumetric efficiency of R513A is higher than that of R134a by approximately 4%.
- Global efficiency of the two refrigerants is similar.
- The R513A is non-flammable and azeotropic and is an environment-friendly refrigerant, with no ODP and low GWP. It can be used as an alternative to R134a in MACs under summer conditions.

Acknowledgment

This work is supported by Young Talents Support Project in Henan Province (No. 2020HYTP022), Key Scientific Research Project of College in Henan Province (No. 20A470017, 19A470011), Independent Innovation Project of Zhongyuan University of Technology (No. K2019YY012), Science and Technology Guidance Project of China National Textile And Apparel Council (No. 2019072), Zhihui Zhengzhou 1125 Talent Gathering Plan Innovation and Entrepreneurship Leading.

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Paper submitted: March 8, 2020
Paper revised: June 20, 2020
Paper accepted: June 20, 2020